

A search for the decay $B^+ \rightarrow K^+ \nu \bar{\nu}$

B. Aubert,¹ R. Barate,¹ D. Boutigny,¹ F. Couderc,¹ J.-M. Gaillard,¹ A. Hicheur,¹ Y. Karyotakis,¹ J. P. Lees,¹
V. Tisserand,¹ A. Zghiche,¹ A. Palano,² A. Pompili,² J. C. Chen,³ N. D. Qi,³ G. Rong,³ P. Wang,³ Y. S. Zhu,³
G. Eigen,⁴ I. Ofte,⁴ B. Stugu,⁴ G. S. Abrams,⁵ A. W. Borgland,⁵ A. B. Breon,⁵ D. N. Brown,⁵ J. Button-Shafer,⁵
R. N. Cahn,⁵ E. Charles,⁵ C. T. Day,⁵ M. S. Gill,⁵ A. V. Gritsan,⁵ Y. Groysman,⁵ R. G. Jacobsen,⁵ R. W. Kadel,⁵
J. Kadyk,⁵ L. T. Kerth,⁵ Yu. G. Kolomensky,⁵ G. Kukartsev,⁵ G. Lynch,⁵ L. M. Mir,⁵ P. J. Oddone,⁵
T. J. Orimoto,⁵ M. Pripstein,⁵ N. A. Roe,⁵ M. T. Ronan,⁵ V. G. Shelkov,⁵ W. A. Wenzel,⁵ M. Barrett,⁶
K. E. Ford,⁶ T. J. Harrison,⁶ A. J. Hart,⁶ C. M. Hawkes,⁶ S. E. Morgan,⁶ A. T. Watson,⁶ M. Fritsch,⁷ K. Goetzen,⁷
T. Held,⁷ H. Koch,⁷ B. Lewandowski,⁷ M. Pelizaeus,⁷ M. Steinke,⁷ J. T. Boyd,⁸ N. Chevalier,⁸ W. N. Cottingham,⁸
M. P. Kelly,⁸ T. E. Latham,⁸ F. F. Wilson,⁸ T. Cuhadar-Donszelmann,⁹ C. Hearty,⁹ N. S. Knecht,⁹ T. S. Mattison,⁹
J. A. McKenna,⁹ D. Thiessen,⁹ A. Khan,¹⁰ P. Kyberd,¹⁰ L. Teodorescu,¹⁰ A. E. Blinov,¹¹ V. E. Blinov,¹¹
V. P. Druzhinin,¹¹ V. B. Golubev,¹¹ V. N. Ivanchenko,¹¹ E. A. Kravchenko,¹¹ A. P. Onuchin,¹¹ S. I. Serednyakov,¹¹
Yu. I. Skovpen,¹¹ E. P. Solodov,¹¹ A. N. Yushkov,¹¹ D. Best,¹² M. Bruinsma,¹² M. Chao,¹² I. Eschrich,¹²
D. Kirkby,¹² A. J. Lankford,¹² M. Mandelkern,¹² R. K. Mommsen,¹² W. Roethel,¹² D. P. Stoker,¹² C. Buchanan,¹³
B. L. Hartfiel,¹³ S. D. Foulkes,¹⁴ J. W. Gary,¹⁴ B. C. Shen,¹⁴ K. Wang,¹⁴ D. del Re,¹⁵ H. K. Hadavand,¹⁵
E. J. Hill,¹⁵ D. B. MacFarlane,¹⁵ H. P. Paar,¹⁵ Sh. Rahatlou,¹⁵ V. Sharma,¹⁵ J. W. Berryhill,¹⁶ C. Campagnari,¹⁶
B. Dahmes,¹⁶ O. Long,¹⁶ A. Lu,¹⁶ M. A. Mazur,¹⁶ J. D. Richman,¹⁶ W. Verkerke,¹⁶ T. W. Beck,¹⁷ A. M. Eisner,¹⁷
C. A. Heusch,¹⁷ J. Kroseberg,¹⁷ W. S. Lockman,¹⁷ G. Nesom,¹⁷ T. Schalk,¹⁷ B. A. Schumm,¹⁷ A. Seiden,¹⁷
P. Spradlin,¹⁷ D. C. Williams,¹⁷ M. G. Wilson,¹⁷ J. Albert,¹⁸ E. Chen,¹⁸ G. P. Dubois-Felsmann,¹⁸
A. Dvoretzkii,¹⁸ D. G. Hitlin,¹⁸ I. Narsky,¹⁸ T. Piatenko,¹⁸ F. C. Porter,¹⁸ A. Ryd,¹⁸ A. Samuel,¹⁸ S. Yang,¹⁸
S. Jayatilake,¹⁹ G. Mancinelli,¹⁹ B. T. Meadows,¹⁹ M. D. Sokoloff,¹⁹ T. Abe,²⁰ F. Blanc,²⁰ P. Bloom,²⁰
S. Chen,²⁰ W. T. Ford,²⁰ U. Nauenberg,²⁰ A. Olivas,²⁰ P. Rankin,²⁰ J. G. Smith,²⁰ J. Zhang,²⁰ L. Zhang,²⁰
A. Chen,²¹ J. L. Harton,²¹ A. Soffer,²¹ W. H. Toki,²¹ R. J. Wilson,²¹ Q. Zeng,²¹ D. Altenburg,²² T. Brandt,²²
J. Brose,²² M. Dickopp,²² E. Feltresi,²² A. Hauke,²² H. M. Lacker,²² R. Müller-Pfefferkorn,²² R. Nogowski,²²
S. Otto,²² A. Petzold,²² J. Schubert,²² K. R. Schubert,²² R. Schwierz,²² B. Spaan,²² J. E. Sundermann,²²
D. Bernard,²³ G. R. Bonneaud,²³ F. Brochard,²³ P. Grenier,²³ S. Schrenk,²³ Ch. Thiebaux,²³ G. Vasileiadis,²³
M. Verderi,²³ D. J. Bard,²⁴ P. J. Clark,²⁴ D. Lavin,²⁴ F. Muheim,²⁴ S. Playfer,²⁴ Y. Xie,²⁴ M. Andreotti,²⁵
V. Azzolini,²⁵ D. Bettoni,²⁵ C. Bozzi,²⁵ R. Calabrese,²⁵ G. Cibinetto,²⁵ E. Luppi,²⁵ M. Negrini,²⁵ L. Piemontese,²⁵
A. Sarti,²⁵ E. Treadwell,²⁶ F. Anulli,²⁷ R. Baldini-Ferrolì,²⁷ A. Calcaterra,²⁷ R. de Sangro,²⁷ G. Finocchiaro,²⁷
P. Patteri,²⁷ I. M. Peruzzi,²⁷ M. Piccolo,²⁷ A. Zallo,²⁷ A. Buzzo,²⁸ R. Capra,²⁸ R. Contri,²⁸ G. Crosetti,²⁸
M. Lo Vetere,²⁸ M. Macri,²⁸ M. R. Monge,²⁸ S. Passaggio,²⁸ C. Patrignani,²⁸ E. Robutti,²⁸ A. Santroni,²⁸
S. Tosi,²⁸ S. Bailey,²⁹ G. Brandenburg,²⁹ K. S. Chaisanguanthum,²⁹ M. Morii,²⁹ E. Won,²⁹ R. S. Dubitzky,³⁰
U. Langenegger,³⁰ W. Bhimji,³¹ D. A. Bowerman,³¹ P. D. Dauncey,³¹ U. Egede,³¹ J. R. Gaillard,³¹ G. W. Morton,³¹
J. A. Nash,³¹ M. B. Nikolich,³¹ G. P. Taylor,³¹ M. J. Charles,³² G. J. Grenier,³² U. Mallik,³² J. Cochran,³³
H. B. Crawley,³³ J. Lamsa,³³ W. T. Meyer,³³ S. Prell,³³ E. I. Rosenberg,³³ A. E. Rubin,³³ J. Yi,³³ M. Biasini,³⁴
R. Covarelli,³⁴ M. Pioppi,³⁴ M. Davier,³⁵ X. Giroux,³⁵ G. Grosdidier,³⁵ A. Höcker,³⁵ S. Laplace,³⁵ F. Le Diberder,³⁵
V. Lepeltier,³⁵ A. M. Lutz,³⁵ T. C. Petersen,³⁵ S. Plaszczynski,³⁵ M. H. Schune,³⁵ L. Tantot,³⁵ G. Wormser,³⁵
C. H. Cheng,³⁶ D. J. Lange,³⁶ M. C. Simani,³⁶ D. M. Wright,³⁶ A. J. Bevan,³⁷ C. A. Chavez,³⁷ J. P. Coleman,³⁷
I. J. Forster,³⁷ J. R. Fry,³⁷ E. Gabathuler,³⁷ R. Gamet,³⁷ D. E. Hutchcroft,³⁷ R. J. Parry,³⁷ D. J. Payne,³⁷
R. J. Sloane,³⁷ C. Touramanis,³⁷ J. J. Back,^{38,*} C. M. Cormack,^{38,*} P. F. Harrison,^{38,*} F. Di Lodovico,³⁸
G. B. Mohanty,^{38,*} C. L. Brown,³⁹ G. Cowan,³⁹ R. L. Flack,³⁹ H. U. Flaecher,³⁹ M. G. Green,³⁹ P. S. Jackson,³⁹
T. R. McMahon,³⁹ S. Ricciardi,³⁹ F. Salvatore,³⁹ M. A. Winter,³⁹ D. Brown,⁴⁰ C. L. Davis,⁴⁰ J. Allison,⁴¹
N. R. Barlow,⁴¹ R. J. Barlow,⁴¹ P. A. Hart,⁴¹ M. C. Hodgkinson,⁴¹ G. D. Lafferty,⁴¹ A. J. Lyon,⁴¹ J. C. Williams,⁴¹
A. Farbin,⁴² W. D. Hulsbergen,⁴² A. Jawahery,⁴² D. Kovalskyi,⁴² C. K. Lae,⁴² V. Lillard,⁴² D. A. Roberts,⁴²
G. Blaylock,⁴³ C. Dallapiccola,⁴³ K. T. Flood,⁴³ S. S. Hertzbach,⁴³ R. Kofler,⁴³ V. B. Koptchev,⁴³ T. B. Moore,⁴³
S. Saremi,⁴³ H. Staengle,⁴³ S. Willocq,⁴³ R. Cowan,⁴⁴ G. Sciolla,⁴⁴ S. J. Sekula,⁴⁴ F. Taylor,⁴⁴ R. K. Yamamoto,⁴⁴
D. J. J. Mangeol,⁴⁵ P. M. Patel,⁴⁵ S. H. Robertson,⁴⁵ A. Lazzaro,⁴⁶ V. Lombardo,⁴⁶ F. Palombo,⁴⁶

J. M. Bauer,⁴⁷ L. Cremaldi,⁴⁷ V. Eschenburg,⁴⁷ R. Godang,⁴⁷ R. Kroeger,⁴⁷ J. Reidy,⁴⁷ D. A. Sanders,⁴⁷ D. J. Summers,⁴⁷ H. W. Zhao,⁴⁷ S. Brunet,⁴⁸ D. Côté,⁴⁸ P. Taras,⁴⁸ H. Nicholson,⁴⁹ N. Cavallo,^{50,†} F. Fabozzi,^{50,†} C. Gatto,⁵⁰ L. Lista,⁵⁰ D. Monorchio,⁵⁰ P. Paolucci,⁵⁰ D. Piccolo,⁵⁰ C. Sciacca,⁵⁰ M. Baak,⁵¹ H. Bulten,⁵¹ G. Raven,⁵¹ H. L. Snoek,⁵¹ L. Wilden,⁵¹ C. P. Jessop,⁵² J. M. LoSecco,⁵² T. Allmendinger,⁵³ K. K. Gan,⁵³ K. Honscheid,⁵³ D. Hufnagel,⁵³ H. Kagan,⁵³ R. Kass,⁵³ T. Pulliam,⁵³ A. M. Rahimi,⁵³ R. Ter-Antonyan,⁵³ Q. K. Wong,⁵³ J. Brau,⁵⁴ R. Frey,⁵⁴ O. Igonkina,⁵⁴ C. T. Potter,⁵⁴ N. B. Sinev,⁵⁴ D. Strom,⁵⁴ E. Torrence,⁵⁴ F. Colecchia,⁵⁵ A. Dorigo,⁵⁵ F. Galeazzi,⁵⁵ M. Margoni,⁵⁵ M. Morandin,⁵⁵ M. Posocco,⁵⁵ M. Rotondo,⁵⁵ F. Simonetto,⁵⁵ R. Stroili,⁵⁵ G. Tiozzo,⁵⁵ C. Voci,⁵⁵ M. Benayoun,⁵⁶ H. Briand,⁵⁶ J. Chauveau,⁵⁶ P. David,⁵⁶ Ch. de la Vaissière,⁵⁶ L. Del Buono,⁵⁶ O. Hamon,⁵⁶ M. J. J. John,⁵⁶ Ph. Leruste,⁵⁶ J. Malcles,⁵⁶ J. Ocariz,⁵⁶ M. Pivk,⁵⁶ L. Roos,⁵⁶ S. T'Jampens,⁵⁶ G. Therin,⁵⁶ P. F. Manfredi,⁵⁷ V. Re,⁵⁷ P. K. Behera,⁵⁸ L. Gladney,⁵⁸ Q. H. Guo,⁵⁸ J. Panetta,⁵⁸ C. Angelini,⁵⁹ G. Batignani,⁵⁹ S. Bettarini,⁵⁹ M. Bondioli,⁵⁹ F. Bucci,⁵⁹ G. Calderini,⁵⁹ M. Carpinelli,⁵⁹ F. Forti,⁵⁹ M. A. Giorgi,⁵⁹ A. Lusiani,⁵⁹ G. Marchiori,⁵⁹ F. Martinez-Vidal,^{59,‡} M. Morganti,⁵⁹ N. Neri,⁵⁹ E. Paoloni,⁵⁹ M. Rama,⁵⁹ G. Rizzo,⁵⁹ F. Sandrelli,⁵⁹ J. Walsh,⁵⁹ M. Haire,⁶⁰ D. Judd,⁶⁰ K. Paick,⁶⁰ D. E. Wagoner,⁶⁰ N. Danielson,⁶¹ P. Elmer,⁶¹ Y. P. Lau,⁶¹ C. Lu,⁶¹ V. Miftakov,⁶¹ J. Olsen,⁶¹ A. J. S. Smith,⁶¹ A. V. Telnov,⁶¹ F. Bellini,⁶² G. Cavoto,^{61,62} R. Faccini,⁶² F. Ferrarotto,⁶² F. Ferroni,⁶² M. Gaspero,⁶² L. Li Gioi,⁶² M. A. Mazzoni,⁶² S. Morganti,⁶² M. Pierini,⁶² G. Piredda,⁶² F. Safai Tehrani,⁶² C. Voena,⁶² S. Christ,⁶³ G. Wagner,⁶³ R. Waldi,⁶³ T. Adye,⁶⁴ N. De Groot,⁶⁴ B. Franek,⁶⁴ N. I. Geddes,⁶⁴ G. P. Gopal,⁶⁴ E. O. Olaiya,⁶⁴ R. Aleksan,⁶⁵ S. Emery,⁶⁵ A. Gaidot,⁶⁵ S. F. Ganzhur,⁶⁵ P.-F. Giraud,⁶⁵ G. Hamel de Monchenault,⁶⁵ W. Kozanecki,⁶⁵ M. Legendre,⁶⁵ G. W. London,⁶⁵ B. Mayer,⁶⁵ G. Schott,⁶⁵ G. Vasseur,⁶⁵ Ch. Yèche,⁶⁵ M. Zito,⁶⁵ M. V. Purohit,⁶⁶ A. W. Weidemann,⁶⁶ J. R. Wilson,⁶⁶ F. X. Yumiceva,⁶⁶ D. Aston,⁶⁷ R. Bartoldus,⁶⁷ N. Berger,⁶⁷ A. M. Boyarski,⁶⁷ O. L. Buchmueller,⁶⁷ R. Claus,⁶⁷ M. R. Convery,⁶⁷ M. Cristinziani,⁶⁷ G. De Nardo,⁶⁷ D. Dong,⁶⁷ J. Dorfan,⁶⁷ D. Dujmic,⁶⁷ W. Dunwoodie,⁶⁷ E. E. Elsen,⁶⁷ S. Fan,⁶⁷ R. C. Field,⁶⁷ T. Glanzman,⁶⁷ S. J. Gowdy,⁶⁷ T. Hadig,⁶⁷ V. Halyo,⁶⁷ C. Hast,⁶⁷ T. Hryn'ova,⁶⁷ W. R. Innes,⁶⁷ M. H. Kelsey,⁶⁷ P. Kim,⁶⁷ M. L. Kocian,⁶⁷ D. W. G. S. Leith,⁶⁷ J. Libby,⁶⁷ S. Luitz,⁶⁷ V. Luth,⁶⁷ H. L. Lynch,⁶⁷ H. Marsiske,⁶⁷ R. Messner,⁶⁷ D. R. Muller,⁶⁷ C. P. O'Grady,⁶⁷ V. E. Ozcan,⁶⁷ A. Perazzo,⁶⁷ M. Perl,⁶⁷ S. Petrak,⁶⁷ B. N. Ratcliff,⁶⁷ A. Roodman,⁶⁷ A. A. Salnikov,⁶⁷ R. H. Schindler,⁶⁷ J. Schwiening,⁶⁷ G. Simi,⁶⁷ A. Snyder,⁶⁷ A. Soha,⁶⁷ J. Stelzer,⁶⁷ D. Su,⁶⁷ M. K. Sullivan,⁶⁷ J. Va'vra,⁶⁷ S. R. Wagner,⁶⁷ M. Weaver,⁶⁷ A. J. R. Weinstein,⁶⁷ W. J. Wisniewski,⁶⁷ M. Wittgen,⁶⁷ D. H. Wright,⁶⁷ A. K. Yarritu,⁶⁷ C. C. Young,⁶⁷ P. R. Burchat,⁶⁸ A. J. Edwards,⁶⁸ T. I. Meyer,⁶⁸ B. A. Petersen,⁶⁸ C. Roat,⁶⁸ S. Ahmed,⁶⁹ M. S. Alam,⁶⁹ J. A. Ernst,⁶⁹ M. A. Saeed,⁶⁹ M. Saleem,⁶⁹ F. R. Wappler,⁶⁹ W. Bugg,⁷⁰ M. Krishnamurthy,⁷⁰ S. M. Spanier,⁷⁰ R. Eckmann,⁷¹ H. Kim,⁷¹ J. L. Ritchie,⁷¹ A. Satpathy,⁷¹ R. F. Schwitters,⁷¹ J. M. Izen,⁷² I. Kitayama,⁷² X. C. Lou,⁷² S. Ye,⁷² F. Bianchi,⁷³ M. Bona,⁷³ F. Gallo,⁷³ D. Gamba,⁷³ L. Bosisio,⁷⁴ C. Cartaro,⁷⁴ F. Cossutti,⁷⁴ G. Della Ricca,⁷⁴ S. Dittongo,⁷⁴ S. Grancagnolo,⁷⁴ L. Lanceri,⁷⁴ P. Poropat,^{74,§} L. Vitale,⁷⁴ G. Vuagnin,⁷⁴ R. S. Panvini,⁷⁵ Sw. Banerjee,⁷⁶ C. M. Brown,⁷⁶ D. Fortin,⁷⁶ P. D. Jackson,⁷⁶ R. Kowalewski,⁷⁶ J. M. Roney,⁷⁶ R. J. Sobie,⁷⁶ H. R. Band,⁷⁷ B. Cheng,⁷⁷ S. Dasu,⁷⁷ M. Datta,⁷⁷ A. M. Eichenbaum,⁷⁷ M. Graham,⁷⁷ J. J. Hollar,⁷⁷ J. R. Johnson,⁷⁷ P. E. Kutter,⁷⁷ H. Li,⁷⁷ R. Liu,⁷⁷ A. Mihalyi,⁷⁷ A. K. Mohapatra,⁷⁷ Y. Pan,⁷⁷ R. Prepost,⁷⁷ P. Tan,⁷⁷ J. H. von Wimmersperg-Toeller,⁷⁷ J. Wu,⁷⁷ S. L. Wu,⁷⁷ Z. Yu,⁷⁷ M. G. Greene,⁷⁸ and H. Neal⁷⁸

(The BABAR Collaboration)

¹Laboratoire de Physique des Particules, F-74941 Annecy-le-Vieux, France

²Università di Bari, Dipartimento di Fisica and INFN, I-70126 Bari, Italy

³Institute of High Energy Physics, Beijing 100039, China

⁴University of Bergen, Inst. of Physics, N-5007 Bergen, Norway

⁵Lawrence Berkeley National Laboratory and University of California, Berkeley, CA 94720, USA

⁶University of Birmingham, Birmingham, B15 2TT, United Kingdom

⁷Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany

⁸University of Bristol, Bristol BS8 1TL, United Kingdom

⁹University of British Columbia, Vancouver, BC, Canada V6T 1Z1

¹⁰Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom

¹¹Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia

¹²University of California at Irvine, Irvine, CA 92697, USA

¹³University of California at Los Angeles, Los Angeles, CA 90024, USA

¹⁴University of California at Riverside, Riverside, CA 92521, USA

¹⁵University of California at San Diego, La Jolla, CA 92093, USA

¹⁶University of California at Santa Barbara, Santa Barbara, CA 93106, USA

- ¹⁷University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, CA 95064, USA
- ¹⁸California Institute of Technology, Pasadena, CA 91125, USA
- ¹⁹University of Cincinnati, Cincinnati, OH 45221, USA
- ²⁰University of Colorado, Boulder, CO 80309, USA
- ²¹Colorado State University, Fort Collins, CO 80523, USA
- ²²Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany
- ²³Ecole Polytechnique, LLR, F-91128 Palaiseau, France
- ²⁴University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
- ²⁵Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy
- ²⁶Florida A&M University, Tallahassee, FL 32307, USA
- ²⁷Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy
- ²⁸Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy
- ²⁹Harvard University, Cambridge, MA 02138, USA
- ³⁰Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany
- ³¹Imperial College London, London, SW7 2AZ, United Kingdom
- ³²University of Iowa, Iowa City, IA 52242, USA
- ³³Iowa State University, Ames, IA 50011-3160, USA
- ³⁴Università di Perugia, Dipartimento di Fisica and INFN, I-06100 Perugia, Italy
- ³⁵Laboratoire de l'Accélérateur Linéaire, F-91898 Orsay, France
- ³⁶Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
- ³⁷University of Liverpool, Liverpool L69 7ZE, United Kingdom
- ³⁸Queen Mary, University of London, E1 4NS, United Kingdom
- ³⁹University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
- ⁴⁰University of Louisville, Louisville, KY 40292, USA
- ⁴¹University of Manchester, Manchester M13 9PL, United Kingdom
- ⁴²University of Maryland, College Park, MD 20742, USA
- ⁴³University of Massachusetts, Amherst, MA 01003, USA
- ⁴⁴Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, MA 02139, USA
- ⁴⁵McGill University, Montréal, QC, Canada H3A 2T8
- ⁴⁶Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy
- ⁴⁷University of Mississippi, University, MS 38677, USA
- ⁴⁸Université de Montréal, Laboratoire René J. A. Lévesque, Montréal, QC, Canada H3C 3J7
- ⁴⁹Mount Holyoke College, South Hadley, MA 01075, USA
- ⁵⁰Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy
- ⁵¹NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
- ⁵²University of Notre Dame, Notre Dame, IN 46556, USA
- ⁵³Ohio State University, Columbus, OH 43210, USA
- ⁵⁴University of Oregon, Eugene, OR 97403, USA
- ⁵⁵Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy
- ⁵⁶Universités Paris VI et VII, Laboratoire de Physique Nucléaire et de Hautes Energies, F-75252 Paris, France
- ⁵⁷Università di Pavia, Dipartimento di Elettronica and INFN, I-27100 Pavia, Italy
- ⁵⁸University of Pennsylvania, Philadelphia, PA 19104, USA
- ⁵⁹Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy
- ⁶⁰Prairie View A&M University, Prairie View, TX 77446, USA
- ⁶¹Princeton University, Princeton, NJ 08544, USA
- ⁶²Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy
- ⁶³Universität Rostock, D-18051 Rostock, Germany
- ⁶⁴Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
- ⁶⁵DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France
- ⁶⁶University of South Carolina, Columbia, SC 29208, USA
- ⁶⁷Stanford Linear Accelerator Center, Stanford, CA 94309, USA
- ⁶⁸Stanford University, Stanford, CA 94305-4060, USA
- ⁶⁹State University of New York, Albany, NY 12222, USA
- ⁷⁰University of Tennessee, Knoxville, TN 37996, USA
- ⁷¹University of Texas at Austin, Austin, TX 78712, USA
- ⁷²University of Texas at Dallas, Richardson, TX 75083, USA
- ⁷³Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy
- ⁷⁴Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy
- ⁷⁵Vanderbilt University, Nashville, TN 37235, USA
- ⁷⁶University of Victoria, Victoria, BC, Canada V8W 3P6
- ⁷⁷University of Wisconsin, Madison, WI 53706, USA
- ⁷⁸Yale University, New Haven, CT 06511, USA
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We search for the rare flavor-changing neutral-current decay $B^+ \rightarrow K^+ \nu \bar{\nu}$ in a data sample of 82 fb^{-1} collected with the *BABAR* detector at the PEP-II B-factory. Signal events are selected by examining the properties of the system recoiling against either a reconstructed hadronic or semileptonic charged- B decay. Using these two independent samples we obtain a combined limit of $\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu}) < 5.2 \times 10^{-5}$ at the 90% confidence level. In addition, by selecting for pions rather than kaons, we obtain a limit of $\mathcal{B}(B^+ \rightarrow \pi^+ \nu \bar{\nu}) < 1.0 \times 10^{-4}$ using only the hadronic B reconstruction method.

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Flavor-changing neutral-current transitions such as $b \rightarrow s \nu \bar{\nu}$ and $b \rightarrow d \nu \bar{\nu}$ occur in the Standard Model (SM) via one-loop box or electroweak penguin diagrams with virtual heavy particles in the loops. Therefore they are expected to be highly suppressed. Because heavy non-SM particles could contribute additional loop diagrams, various new physics scenarios can potentially lead to significant enhancements in the observed rates [1, 2]. Theoretical uncertainties on $b \rightarrow s \nu \bar{\nu}$ are much smaller than the corresponding $b \rightarrow s \ell^+ \ell^-$ modes due to the absence of a photonic penguin contribution and hadronic long distance effects [3]. The SM $B^+ \rightarrow K^+ \nu \bar{\nu}$ branching fraction has been estimated to be $(3.8_{-0.6}^{+1.2}) \times 10^{-6}$ [3, 4], while the most stringent published experimental limit is $\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu}) < 2.4 \times 10^{-4}$ at the 90% confidence level (C.L.) [5]. There is additional suppression of $b \rightarrow d \nu \bar{\nu}$ processes relative to $b \rightarrow s \nu \bar{\nu}$ from the Cabibbo-Kobayashi-Maskawa matrix-element ratio $|V_{td}|^2/|V_{ts}|^2$ [6].

In this work we report the results of a search for the exclusive decay mode $B^+ \rightarrow K^+ \nu \bar{\nu}$. By modifying the particle identification (PID) criteria used in the search, we additionally obtain a limit on the related decay $B^+ \rightarrow \pi^+ \nu \bar{\nu}$. Charge conjugate modes are included implicitly throughout this paper and all kinematic quantities are expressed in the CM frame (i.e. the $\Upsilon(4S)$ rest frame) unless otherwise specified.

The data used in this analysis were collected with the *BABAR* detector [7] at the PEP-II asymmetric-energy e^+e^- storage ring. The results are based on a data sample of 89 million $B\bar{B}$ events, corresponding to an integrated luminosity of 82 fb^{-1} collected at the $\Upsilon(4S)$ resonance. An additional sample of 9.6 fb^{-1} was collected at a center-of-mass (CM) energy approximately 40 MeV below $B\bar{B}$ threshold. We used this sample to study continuum events, $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s$ and c). Charged-particle tracking and dE/dx measurements for particle identification (PID) are provided by a five-layer double-sided silicon vertex tracker and a 40-layer drift chamber contained within the magnetic field of a 1.5 T superconducting solenoid. A ring-imaging Cherenkov detector (DIRC) provides charged $K-\pi$ separation of greater than 3σ over the momentum range of interest for this analysis. The energies of neutral particles are measured by an electromagnetic calorimeter (EMC) consisting of 6580 CsI(Tl) crystals. The magnetic flux return of the

solenoid is instrumented with resistive plate chambers in order to provide muon identification. A full *BABAR* detector Monte Carlo (MC) simulation based on GEANT4 [8] is used to evaluate signal efficiencies and to identify and study background sources.

The presence of two neutrinos in the final state precludes the direct reconstruction of the $B^+ \rightarrow K^+ \nu \bar{\nu}$ signal mode. Instead, the B^- meson from an $\Upsilon(4S) \rightarrow B^+ B^-$ event is reconstructed in one of many semileptonic or hadronic decay modes, then all remaining charged and neutral particles in that event are examined under the assumption that they are attributable to the decay of the accompanying B .

The B^- reconstruction proceeds by combining a D^0 candidate with either a single identified charged lepton or a combination X_{had}^- of charged and neutral hadrons. The resulting semileptonic and hadronic charged- B samples are referred to as B_{sl}^- and B_{had}^- throughout this paper. The D^0 candidates are reconstructed by selecting combinations of identified pions and kaons that yield an invariant mass within approximately 3σ of the expected D^0 mass in the modes $K^-\pi^+$, $K^-\pi^+\pi^0$ and $K^-\pi^+\pi^+\pi^-$. For B_{had}^- reconstruction, $D^0 \rightarrow K_s^0 \pi^+ \pi^-$ is also used.

Photon candidates are obtained from EMC clusters with laboratory-frame energy greater than 30 MeV and no associated charged track. Photon pairs that combine to yield $\gamma\gamma$ invariant masses between $115 \text{ MeV}/c^2$ and $150 \text{ MeV}/c^2$ and total energy greater than 200 MeV are considered to be π^0 candidates.

The B_{sl}^- candidates are reconstructed by combining a D^0 candidate having a momentum $p_{D^0} > 0.5 \text{ GeV}/c$ with a lepton candidate of momentum $p_\ell > 1.35 \text{ GeV}/c$ that satisfies either electron or muon identification criteria. The invariant mass, $m_{D\ell}$, of the $D^0\ell$ candidate is required to be greater than $3.0 \text{ GeV}/c^2$. Under the assumption that the neutrino is the only missing particle, the cosine of the angle between the inferred direction of the reconstructed B and that of the lepton- D^0 combination, described by the four vector $(E_{D\ell}, \mathbf{p}_{D\ell})$, is

$$\cos \theta_{B,D\ell} \equiv \frac{2 E_{\text{beam}} \cdot E_{D\ell} - m_B^2 - m_{D\ell}^2}{2 |\mathbf{p}_{D\ell}| \cdot \sqrt{E_{\text{beam}}^2 - m_B^2}}, \quad (1)$$

where m_B is the nominal B meson mass and E_{beam} and $\sqrt{E_{\text{beam}}^2 - m_B^2}$ are the expected B -meson energy and momentum, respectively. We use $\cos \theta_{B,D\ell}$ to discriminate against combinatorial backgrounds, for which

$|\cos\theta_{B,D\ell}|$ can exceed unity. We retain events in the interval $-2.5 < \cos\theta_{B,D\ell} < 1.1$ in order to maintain efficiency for $B^- \rightarrow D^{*0}\ell^-\bar{\nu}$ decays in which a π^0 or photon has not been reconstructed as part of the $D\ell$ combination. However events are vetoed if a charged π consistent with $\bar{B}^0 \rightarrow D^{*+}\ell^-\bar{\nu}$ is identified. If more than one $D\ell$ candidate is reconstructed in a given event, the candidate with the smallest $|\cos\theta_{B,D\ell}|$ is retained.

Reconstructed B_{had}^- decays are obtained by combining a reconstructed D^0 candidate with a hadronic system X_{had}^- composed of up to five mesons (π^\pm , K^\pm , and π^0), including up to two π^0 candidates. We define the kinematic variables $m_{ES} \equiv \sqrt{E_{\text{beam}}^2 - \mathbf{p}_B^2}$ and $\Delta E \equiv E_B - E_{\text{beam}}$ where \mathbf{p}_B and E_B are the momentum and the energy of the B_{had}^- candidate. The X_{had}^- system is selected by requiring that the resulting B_{had}^- candidate lies within $-1.8 < \Delta E < 0.6$ GeV. If multiple B_{had}^- candidates are identified in an event, only the one with ΔE closest to zero is retained. The m_{ES} distribution of reconstructed B_{had}^- candidates is shown in Fig. 1b. B_{had}^- candidates in the signal region, $5.272 < m_{ES} < 5.288$ GeV/ c^2 , are used for the $B^+ \rightarrow K^+\nu\bar{\nu}$ signal selection. Candidates in the sideband region, $5.225 < m_{ES} < 5.265$ GeV/ c^2 , are retained for background studies.

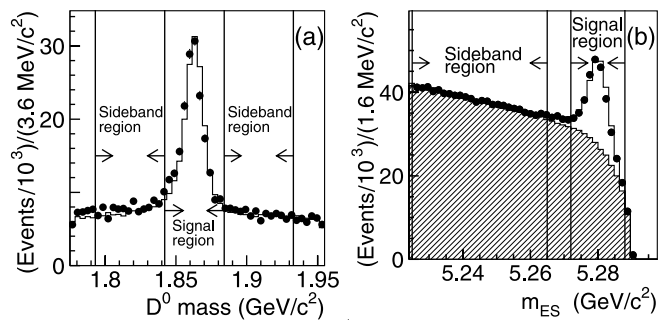


FIG. 1: (a) The D^0 mass distribution for $D^0 \rightarrow K^-\pi^+$ decays used for B_{sl}^- reconstruction. Data are shown as points and the total background MC is shown as a solid histogram. (b) The m_{ES} distribution of B_{had}^- events for data (points) and $B\bar{B}$ MC (solid histogram). Continuum background has been subtracted from the on-resonance data using off-resonance data. The hatched histogram represents the estimated combinatorial background from $B\bar{B}$ decays.

Combinatorial backgrounds from continuum events are reduced in both the B_{sl}^- and B_{had}^- samples by requiring $|\cos\theta_T| < 0.8$, where θ_T is the angle between the thrust axes defined by the B_{sl}^- or B_{had}^- daughter particles, and by all other tracks and clusters in the event. Continuum events peak at $|\cos\theta_T| = 1$, while the distribution is approximately flat for $B\bar{B}$ events. Backgrounds from QED processes are strongly suppressed by the B^- reconstruction procedures and are negligible in this analysis.

The B_{had}^- reconstruction efficiency for events containing a $B^+ \rightarrow K^+\nu\bar{\nu}$ (signal) decay is determined from signal MC simulation after validating the yield

from B^+B^- MC simulation against data. This procedure compensates for differences in the B_{had}^- reconstruction efficiency in the low-multiplicity environment of $B^+ \rightarrow K^+\nu\bar{\nu}$ events compared with the generic B^+B^- environment. The B_{had}^- and B_{sl}^- reconstruction efficiencies in MC are additionally validated by comparing the yield of events in which a $B^+ \rightarrow \bar{D}^0\ell^+\nu$ has been reconstructed in addition to the B_{had}^- or B_{sl}^- . The B_{sl}^- and B_{had}^- reconstruction procedures result in raw yields of approximately 5800 $B_{\text{sl}}^-/\text{fb}^{-1}$ and 2200 $B_{\text{had}}^-/\text{fb}^{-1}$. Relative systematic uncertainties of 4.5% (7%) are estimated for the overall B_{sl}^- (B_{had}^-) yields.

Events that contain a reconstructed B^- are examined for evidence of a $B^+ \rightarrow K^+\nu\bar{\nu}$ decay. Tracks and EMC clusters not already utilized for the B^- reconstruction are assumed to be the daughters of the signal candidate B decay. Signal candidate events are required to possess exactly one additional track with charge opposite that of the reconstructed B^- . The track is additionally required to satisfy K PID criteria and to have momentum p_K greater than 1.25 GeV/ c .

In addition to this track, $B^+ \rightarrow K^+\nu\bar{\nu}$ events contain an average of approximately 200 MeV of EMC energy from hadronic shower fragments, photons from unreconstructed $D^* \rightarrow D^0\gamma/\pi^0$ transitions in the B^- candidate, and beam-related background photons. The total calorimeter energy attributed to the signal decay, E_{extra} , is computed by summing all EMC clusters that are not associated either with the decay daughters of the B^- or with the signal track. Signal events are required to have $E_{\text{extra}} < 250$ MeV. The E_{extra} distributions are shown in Fig. 2 for B_{sl}^- and B_{had}^- events with one additional track that has been identified as a kaon. The B_{had}^- analysis additionally requires that there are six or fewer clusters contributing to E_{extra} , and that no pair of these clusters can be combined to form a π^0 candidate.

The total $B^+ \rightarrow K^+\nu\bar{\nu}$ signal selection efficiencies, including the B^- reconstruction, are estimated to be $\varepsilon_K = (0.115 \pm 0.009)\%$ for B_{sl}^- and $\varepsilon_K = (0.055 \pm 0.005)\%$ for B_{had}^- events. The quoted errors are the quadratic sum of statistical and systematic uncertainties. Theoretical uncertainties in the K^\pm energy spectrum result in a 1.3% uncertainty on the signal efficiency. This uncertainty is evaluated by comparing the p_K spectrum of $B^+ \rightarrow K^+\nu\bar{\nu}$ MC events generated with a phase-space model with the models given in [3, 4]. Additional systematic uncertainties associated with the $B^+ \rightarrow K^+\nu\bar{\nu}$ signal candidate efficiencies include the single track efficiency (1.3%), PID (2%) and EMC energy-modeling (3.8% for B_{sl}^- and 2.3% for B_{had}^-). The EMC energy modeling systematic is determined by evaluating the effect of varying the MC E_{extra} distribution within a range representing the observed level of agreement with data in events with a reconstructed $B^+ \rightarrow \bar{D}^0\ell^+\nu$ (for the B_{sl}^- sample) and in samples containing two or three additional tracks (for the B_{had}^- sample).

Background events can arise either from $B^0\bar{B}^0$ or continuum events in which the B^- candidate is constructed from a random combination of particles, or peaking background events in which the accompanying B^- (or in the case of B_{sl}^- , at least the D^0) has been correctly reconstructed.

In the B_{sl}^- analysis, purely combinatorial backgrounds are estimated by examining sideband regions of the reconstructed D^0 invariant mass distribution, $m_{D^0}^{\text{reco}}$, defined by $3\sigma < |m_{D^0}^{\text{reco}} - m_{D^0}| < 10\sigma$ as is illustrated in Fig. 1a for the $D^0 \rightarrow K^- \pi^+$ mode. The sideband yields are scaled to the signal region under the assumption that the combinatorial component is flat throughout the D^0 mass distribution. This assumption has been validated using samples of events in which two or three tracks not associated with the B^- reconstruction are present. The total combinatorial background in the B_{sl}^- analysis is estimated to be $N_K^{\text{bg}} \geq 3.4 \pm 1.2$. Although the peaking background prediction in the B_{sl}^- analysis have been studied in MC and are shown in Figs 2 and 3, the peaking background in the final selection is not subtracted.

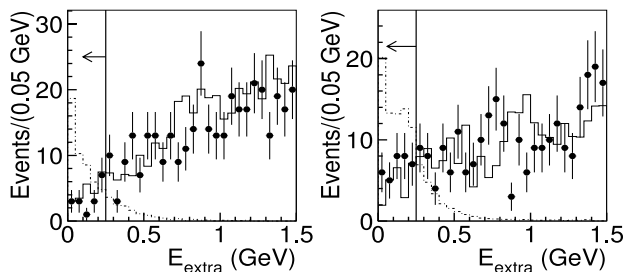


FIG. 2: The E_{extra} distribution for $B^+ \rightarrow K^+ \nu \bar{\nu}$ B_{had}^- (left) and B_{sl}^- (right) events. Events are required to have a reconstructed B^- and exactly one additional track which has been identified as a kaon. No other signal selection cuts have been applied. The data and background MC samples are represented by the points with error bars and solid histograms, respectively. The dotted line indicates the expected $B^+ \rightarrow K^+ \nu \bar{\nu}$ signal distribution from MC

In the B_{had}^- analysis, the combinatorial background can be reliably estimated by extrapolating the observed yields in the m_{ES} sideband region into the m_{ES} signal region, indicated in Fig. 1b, yielding 2.0 ± 0.7 events. The quoted uncertainty is dominated by the sideband data statistics, but includes also the uncertainty in the combinatorial background shape, which is estimated by varying the shape over a range of possible models. The peaking background in the B_{had}^- analysis consists only of $B^+ B^-$ events in which the B_{had}^- has been correctly reconstructed, and is estimated directly from $B^+ B^-$ MC simulation. MC yields are validated by direct comparison with data in samples of events in which the full signal selection is applied, except that either $E_{\text{extra}} > 0.5$ GeV, or more than one track remains after the B^- reconstruction. Uncertainties in the peaking background are dominated

by the MC statistical uncertainty (42%). Other systematic errors include the overall B^- yield (7%), the remaining track multiplicity (5%), the particle mis-identification rates for the K^\pm selection (6.3%), and the EMC-energy modeling (8%). The total peaking background in the B_{had}^- analysis is estimated to be 1.9 ± 0.9 . The total (combinatorial+peaking) background in the B_{had}^- analysis is estimated to be $N_K^{\text{bg}} = 3.9 \pm 1.1$ events.

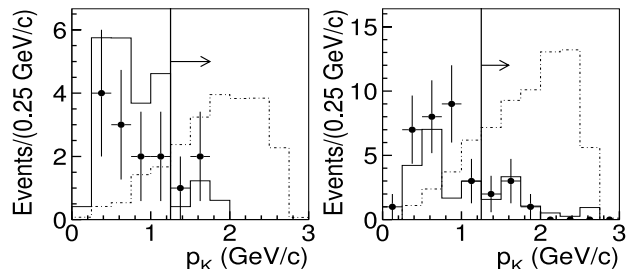


FIG. 3: The p_K distribution for (a) B_{had}^- and (b) B_{sl}^- events after applying the full $B^+ \rightarrow K^+ \nu \bar{\nu}$ selection except for the $p_K > 1.25$ GeV/c requirement. The data and background MC samples are represented by the points and solid histograms respectively. The dotted line indicates the expected signal distribution from MC

The $B^+ \rightarrow K^+ \nu \bar{\nu}$ branching fraction is calculated from

$$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu}) = \frac{N_K^{\text{obs}} - N_K^{\text{bg}}}{N_{B^\pm} \cdot \varepsilon_K} \quad (2)$$

where N_K^{obs} is the total number of observed events in the signal region. $N_{B^\pm} = (88.9 \pm 1.0) \times 10^6$ is the estimated number of B^\pm mesons in the data sample and ε_K is the total efficiency. A total of $N_K^{\text{obs}} = 6$ (3) $B^+ \rightarrow K^+ \nu \bar{\nu}$ candidate events are found in data in the B_{sl}^- (B_{had}^-) analysis. The p_K distributions for $B^+ \rightarrow K^+ \nu \bar{\nu}$ signal events in the B_{sl}^- and B_{had}^- analysis are shown in Fig. 3.

Branching fraction upper limits are computed using a modified frequentist approach, based on Ref. [9], which models systematic uncertainties using Gaussian distributions. For both the B_{sl}^- and B_{had}^- searches, $B^+ \rightarrow K^+ \nu \bar{\nu}$ limits are set at the branching fraction value at which it is estimated that 90% of experiments would produce a yield that is greater than the number of signal events observed. Limits of $\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{sl}} < 7.0 \times 10^{-5}$ and $\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{had}} < 6.7 \times 10^{-5}$ are obtained for the B_{sl}^- and B_{had}^- searches respectively. Since the two tag B samples are statistically independent, we can combine the results of the two analyses to derive a limit of $\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu}) < 5.2 \times 10^{-5}$ at the 90% C.L.

We also report a limit on exclusive $B^+ \rightarrow \pi^+ \nu \bar{\nu}$ branching fraction using only the B_{had}^- sample. The same methodology as for the $B^+ \rightarrow K^+ \nu \bar{\nu}$ search is applied to the $B^+ \rightarrow \pi^+ \nu \bar{\nu}$ search except that the single additional track is required not to satisfy either kaon

or electron PID criteria. The E_{extra} and p_{π} distributions for $B^+ \rightarrow \pi^+ \nu \bar{\nu}$ are shown in Fig. 4. The overall $B^+ \rightarrow \pi^+ \nu \bar{\nu}$ selection efficiency is estimated to be $\varepsilon_{\pi} = (0.065 \pm 0.006)\%$, where the quoted uncertainties include an estimated 2% PID uncertainty, and other contributions to the systematic uncertainty are similar to $B^+ \rightarrow K^+ \nu \bar{\nu}$. The peaking and non-peaking backgrounds are estimated to be 15.1 ± 3.1 events and 9.0 ± 1.8 events respectively, with similar systematic uncertainties to the $B^+ \rightarrow K^+ \nu \bar{\nu}$ analysis. The search selects $N_{\pi}^{\text{obs}} = 21$ candidates in data with an estimated total background of $N_{\pi}^{\text{bg}} = 24.1 \pm 3.6$, resulting an upper limit of $\mathcal{B}(B^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{had}} < 1.0 \times 10^{-4}$ at the 90% C.L..

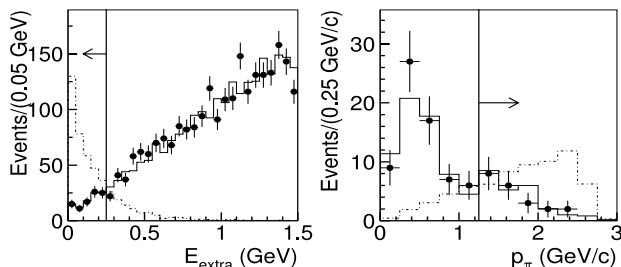


FIG. 4: The E_{extra} (a) and p_{π} (b) distributions for $B^+ \rightarrow \pi^+ \nu \bar{\nu}$ in the B_{had}^- sample. Events shown in the E_{extra} distribution are required to have a reconstructed B^- and exactly one additional track satisfying the pion-selection requirements. The p_{π} distribution has all signal-selection requirements applied other than the p_{π} cut. The data and background MC samples are represented by the points and the solid histogram respectively. The dotted line indicates the expected signal distribution from MC.

We see no evidence for a signal in either of the reported decay modes. The $\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})$ limit reported here is approximately one order of magnitude above the SM prediction. It is the most stringent experimental limit reported to date.

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* Now at Department of Physics, University of Warwick, Coventry, United Kingdom

† Also with Università della Basilicata, Potenza, Italy

‡ Also with IFIC, Instituto de Física Corpuscular, CSIC-Universidad de Valencia, Valencia, Spain

§ Deceased

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